XLA 300: the Fourth-Generation ArF MOPA Light Source for Immersion Lithography

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ABSTRACT

The XLA 300 is Cymer's fourth-generation MOPA-based Argon Fluoride light source built on the production-proven XLA platform. The system is designed to support very high numerical aperture dioptric and catadioptric lens immersion lithography scanners targeted for volume production of semiconductor devices at the 45nm node and beyond. The light source delivers up to 90 W of power with ultra-line narrowed bandwidth as low as 0.12 pm FWHM and 0.25 pm 95% energy integral. The high output power is achieved by advancements in pulse power technology, which allow a 50% increase in repetition rate to 6 kHz. The increased repetition rate, along with pulse stretching, minimizes damage to the scanner system optics at this high power level. New developments in the laser optical systems maintain industry-leading performance for bandwidth stability and high level of polarization despite the increased thermal load generated at the higher repetition rate. The system also features state-of-the-art on-board E95% bandwidth metrology and improved bandwidth stability to provide enhanced CD control. The E95% metrology will move bandwidth monitoring from a quality safeguard flag to a tool that can be used for system feedback and optimization. The proven high power optics technology extends the lifetime of key laser optics modules including the line-narrowing module, and the cost of consumables (CoC) is further reduced by longer chamber lifetimes.

Keywords: excimer laser, 193 nm light source, narrow linewidth, immersion lithography, 6 kHz repetition rate.

1. INTRODUCTION

Cymer's XLA 300 is the fourth generation lithography light source built on the production-proven XLA platform. It is an ultra-line-narrowed ArF laser system based on the MOPA architecture[1]. Earlier XLA systems[2,3,4] have gained rapid acceptance in the industry and are used in volume production in fabs worldwide. The key novel feature of XLA 300 that distinguishes it from its predecessors is the extension of the range of repetition rates up to 6 kHz. The requirements for the light source for immersion lithography at 193 nm include higher output power in order to overcome the additional losses associated with the immersion medium and new polarized illumination designs. The optimal way to increase the output power is without increasing the pulse energy or peak power. This avoids the risk associated with compaction of fused silica in the optics of the lithographic scanner, and allows the scanner manufacturers to minimize the number of the calcium fluoride lens elements. The XLA 300 achieves this by increasing the upper end of the operation repetition rate range to 6 kHz while maintaining the nominal pulse energy at 10 mJ for 60 W power output. The versatile XLA platform allows reconfiguration to achieve specific customer priorities, such as higher output pulse energy up to 15 mJ and power of 90 W. Tradeoffs such as spectral bandwidth versus dose stability can be exploited to create customized configurations in order to best serve the needs of lithography users.

2. DESIGN FEATURES ENABLING HIGHER REPETITION RATE AND OUTPUT POWER

XLA 300 development team has had to address a number of technological challenges. The areas that underwent significant development associated with high repetition rate operation[5] included the following:

- Pulse power system needed revision in order to support higher rep rate operation
- Onboard metrology and control system needed revisions for higher rep rates

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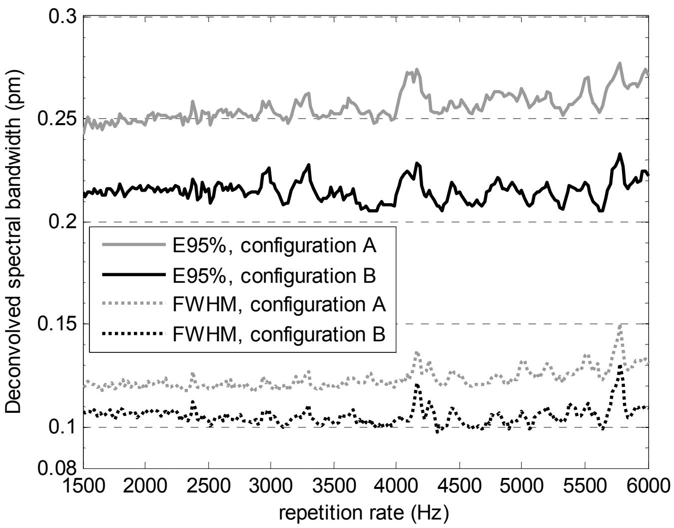

Figure 1. Spectral bandwidth of the XLA 300 laser as a function of repetition rate. High duty cycle repetition rate scan (reaching 75% at 6000 Hz). Measurement with LTB ELIAS II spectrometer. A is the high efficiency configuration; B is the low bandwidth configuration.

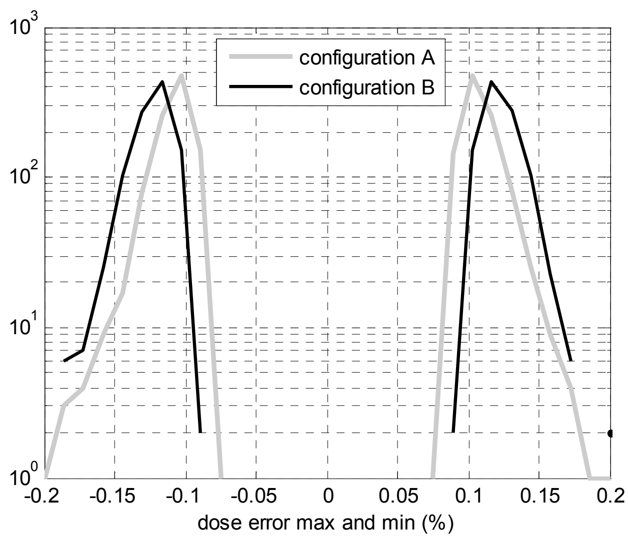

Figure 2. Histogram of the minimum and maximum dose error of the two configurations. 10 ms rectangular exposure window was used. 1000 bursts for each configuration were fired. The firing pattern had 75% duty cycle at 6000 Hz and included pauses to simulate wafer swaps. 10 mJ per pulse energy target.

- Thermal load dissipated by the pulse power subsystem and the chambers increased
- Suppression of acoustic phenomena in the laser chamber affecting the discharge
- Pulse-to-pulse energy stability must be maintained at higher rep rates
- Increase of the speed of the flow of gas across the discharge electrodes, necessary for arc-free discharge, and the concomitant increase of the rate of the dissipated kinetic energy of the gas

2.1. Repetition rate increase enabled by advances in chamber acoustic suppression, fan efficiency, pulse power technology, and the speed of the control system

Acoustic shock waves created by the discharge propagate in the laser gas and can experience several reflections off of the features inside the chamber, creating gas density modulations that will affect the parameters of the next discharge, and the wavefront of generated laser pulse. The phenomenon is characterized by fine dependence on the inter-pulse delay or repetition rate. The most often talked about aspect of these acoustic disturbances is that they affect the laser bandwidth[5,6]. The features associated with these shock-wave round-trips are often somewhat misleadingly called resonances; a more accurate term would be time-of-flight (TOF) resonance, to distinguish them from true resonances of standing waves. Figure 1 shows XLA 300 spectral width as a function of repetition rate. Cymer's RAP technology suppresses a great majority of the acoustic features, while some isolated features remain, most notably in the 5800 Hz vicinity. Laser bandwidth is not the only beam characteristic affected by the TOF resonances. Any beam parameter affected by the wavefront figure of the laser light inherits acoustic features to some degree. This includes such characteristics as divergence (angular extent of the far field beam profile) and symmetry of the near field profiles. Consider the so-called center-centroid deviation. It is an important measure of the symmetry often applied to the one-dimensional cross-sections of the near-field intensity profile of the laser beam. It is the distance between the center-of-mass (centroid) and the center of the profile. The latter is defined as the midpoint between the two points on the edges of the profile where the intensity falls off to 5% of the maximum. The center-centroid deviation as a function of rep rate is

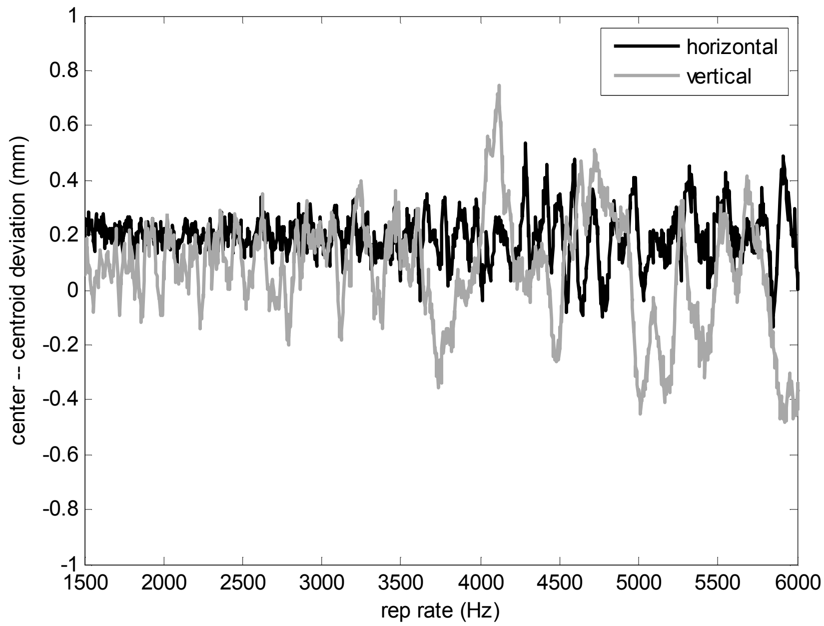

Figure 3. The distance between the center and the centroid of the horizontal and the vertical cross-sections of the near-field beam intensity profile. The center is defined as the midpoint of the full width at 5% of peak intensity. XLA output beam is a square 12*12 mm.

shown in Figure 3. Independent tests confirmed that the features are acoustic in nature. One of the challenges that the chamber development team had to contend with was to keep magnitude of the excursion of this quantity within the limits imposed by the requirements of the next generation scanner illuminators. XLA 300 satisfies these requirements across the 1500—6000 Hz repetition rate range.

Other changes in the Cymer ArF discharge chamber include a more efficient fan enabling higher flow across the electrodes for clearing the discharge products at higher rep rates, and an updated chamber temperature algorithm. The chamber temperature control has to maintain the temperature of the chambers over the interval of duty cycles from near zero to 75%, which correspond to dramatically different rates of heat dissipation. The controller algorithm was fine-tuned to maintain performance across the range of operating conditions. The automated refill procedure responsible for replacing the gas in the chambers has been modified and is now with gas flow circulation compensation. Circulating the chamber gas while refilling proved beneficial, because the temperature sensor is in thermal equilibrium with the circulating gas and is supplying accurate gas temperature readings to the temperature control algorithm, just as it does when the laser is firing. Precise temperature regulation during refill results in accurate pressure measurements and removes the uncertainty in partial pressures that resulted from suboptimal temperature regulation observed in the case of stationary gas. The accuracies of partial pressures of the components of the gas mixture and the total pressure have been improved by a factor of about three to less than 1%.

The pulsed power system underwent incremental, yet significant changes. A new 52 kW high voltage power supply has been developed, as well as a new resonant charger and commutators. The new pulsed power modules have the same form factor as those in XLA 100, and the change in their internal design is transparent to the user. The compression heads have increased in size for improved cooling and better resistance to corona discharge. The new design is a significant step up in the effectiveness of heat removal from the key heat-emitting components such as the reactor cores, as evidenced by reduced component temperatures measured at full duty cycle operation[5].

2.2. Dose stability performance

One of the key advantages of the increased repetition rate is the increase in the number of pulses in an exposure window of fixed duration. However, to realize the improvement in integrated energy dose stability due to the averaging of a

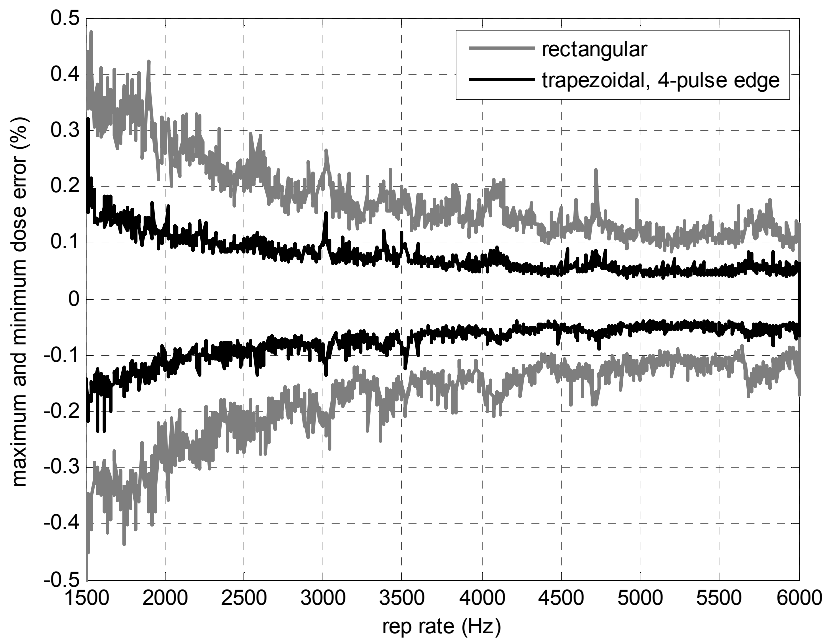

Figure 4. Dose error as a function of repetition rate. Repetition rate scan at high duty cycle (75% at 6000 Hz), 20 Hz interval, 5 bursts per rep rate. The highest and the lowest dose errors are plotted for each burst. The dose error is computed for an exposure window of fixed duration of 10 ms. A rectangular window and a trapezoidal window with 4-pulse-long leading and trailing edges were used. The energy target was 10 mJ per pulse.

larger number of laser pulses, it is necessary to ensure that the energy stability of the discharge does not degrade at higher rep rates, and that the feedback control of the energy is capable of running at higher rep rates. Both of these objectives have been achieved by the XLA 300. The integrated dose stability with closed loop energy control is shown in Figure 4 for a 10 ms window. The best dose stability performance for a fixed time window is achieved in the 4--6 kHz range.

3. SPECTRAL BANDWIDTH AND ITS STABILITY

3.1. New LNM delivers stable bandwidth

Spectral line narrowing in lithography excimer lasers is accomplished by means of a Littrow-mounted diffraction grating used as the rear reflector of the oscillator cavity. The grating, beam expansion optics and the wavelength control actuators comprise the line-narrowing module (LNM), which is a key component of the light source. The LNM has been completely redesigned for XLA 300. The previous generation of Cymer LNM design has approached the fundamental performance limit imposed by diffraction on the available clear aperture of the grating. The new XLA 200 and 300 LNMs uses a higher resolution dispersive element and a completely redesigned wavelength control actuation mechanism. The new LNM is available in several variants designed to operate at different points of the bandwidth versus efficiency tradeoff. This allows the system designer to exploit this tradeoff to create light source configurations for minimum bandwidth, or for best energy stability performance to match the diverging requirements of several models of litho scanners. The data shown in figures 3—5 was obtained using the relatively wideband configuration of XLA 300 (configuration A in figures 1 and 2). The new LNM in combination with the RAP chamber provides excellent stability of bandwidth over a wide variety of operating conditions, including changes in repetition rate, duty cycle and energy target as illustrated in Figure 1 and Figure 5.

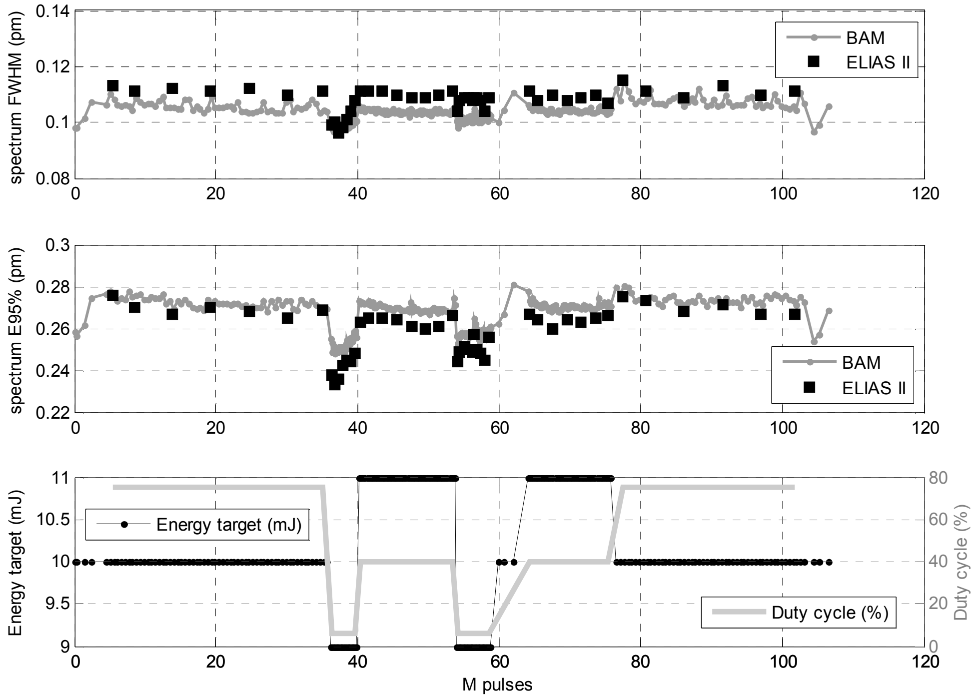

Figure 5. FWFM and E95 % bandwidth of XLA 300 as measured by the BAM and the ELIAS II grating spectrometer in a 100 million pulse gas test. The standard manufacturing acceptance test included several different repetition rates and standby periods.

3.2. Bandwidth metrology

The Cymer Bandwidth Analysis Module (BAM) was introduced in the XLA 105 and XLA 200 products in late 2004 and has proven itself in production environment as a reliable onboard bandwidth metrology tool. The module is a high resolution etalon spectrometer[7] capable of measuring both the E95% (the spectral width containing 95% of energy) and FWHM of the laser spectrum. XLA 300 is equipped with a BAM upgraded for 6 kHz operation. The 6 kHz version, like its predecessor, outputs bandwidth measurements with time resolution comparable to a typical exposure window (approximately 30 laser pulses).

The BAM is calibrated in the factory using an LTB ELIAS II grating spectrometer, the spectral instrument that has become the de-facto standard in DUV bandwidth metrology. XLA 200 and 300 with their ultra-narrow bandwidth have entered the territory where the ELIAS II resolution is a significant fraction of the laser spectrum. A typical instrument function of an ELIAS II has the FWHM of 50 fm and E95% of 250 fm. As can be seen in Figure 5, the BAM performs extremely well in tracking the grating spectrometer. It should be noted, however, that as the spectral line-narrowing advances, the ELIAS II as the standard metrology instrument itself will reach its limit. The uncertainty of the BAM measurements is already *below* the unit-to-unit variability of ELIAS II spectrometer. The question of the next bandwidth standard is rapidly becoming an important challenge. Cymer is investigating technologies and data processing algorithms that can complement the grating spectrometer or improve its performance.

4. WAVELENGTH STABILITY AND WAVELENGTH METROLOGY

4.1. Vibration isolation

The design of XLA vertical optical table and the mechanics of the chamber support have undergone a significant revision. The motivation for this was the need for better mechanical isolation between the various mechanical and optical components of the system to prevent transmission of vibration. The result was a significant improvement of the wavelength stability performance (Figure 6). The rms wavelength error decreased with the new chamber support by between 20 and 40% depending on the model of the LNM used.

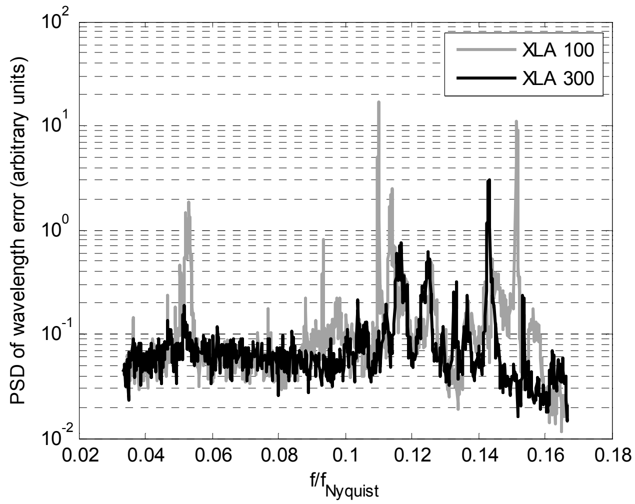

Figure 6. Power spectral density of the wavelength error in the low frequency part of the spectrum. The XLA 300 optical table and chamber support is compared with the predecessor design.

4.2. Wavelength metrology

The onboard wavelength metrology module known as LAM has been upgraded for 6 kHz pulse repetition rate operation. The LAM is an instrument combining an etalon spectrometer for fine wavelength measurement and a coarser resolution grating spectrometer for disambiguating the wavelength corresponding to the etalon fringe pattern, which repeats itself with a periodicity of one free spectral range (FSR). The short-term performance of the module has been characterized. It should be pointed out that assessing the pulse-to-pulse accuracy of a state-of-the-art wavelength meter such as the LAM is challenging due to the fact that no commercially available instruments are capable of measuring DUV wavelength with comparable spectral *and* temporal resolution. The approach chosen for short-term accuracy characterization used two identical LAMs. One was a part of the laser system; the other was installed externally on an optical table. Both instruments were setup to acquire pulse-to-pulse wavelength measurements synchronously, and the laser was then put through an array of firing modes. The difference between the reading of the two instruments combines random errors of both. The standard deviation of the difference is plotted in Figure 7 as a function of the laser wavelength. The error sources include photon shot noise, the readout noise of the photodiode arrays, other electronic noise (A/D conversion, etc.), the fringe-position-dependent error or wavelength systematic, and so on. No effort was made to align the fringe positions of the two etalons. Most if not all error sources for the two units were therefore uncorrelated, and were assumed to contribute to the standard deviation value in quadrature. The performance of a single unit was estimated by dividing the standard deviation by $\sqrt{2}$. The

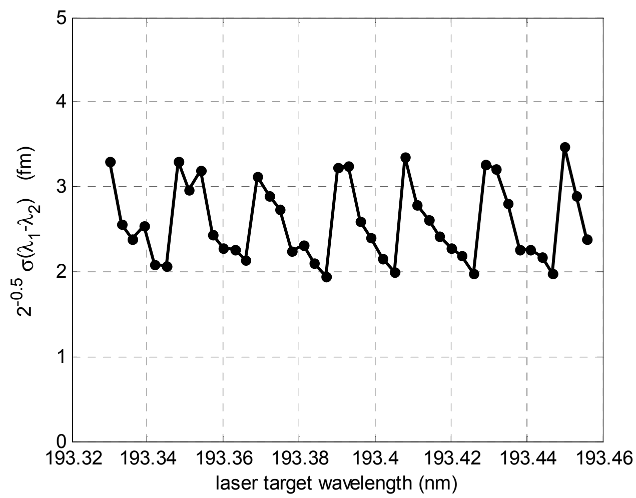

Figure 7. The short-term accuracy of wavelength measurement. Two metrology modules were used (see text). Each point on the plot represents the standard deviation of the difference between the wavelength readings λ_1 and λ_2 of the two instruments, taken over 9000 laser pulses fired at 6 kHz.

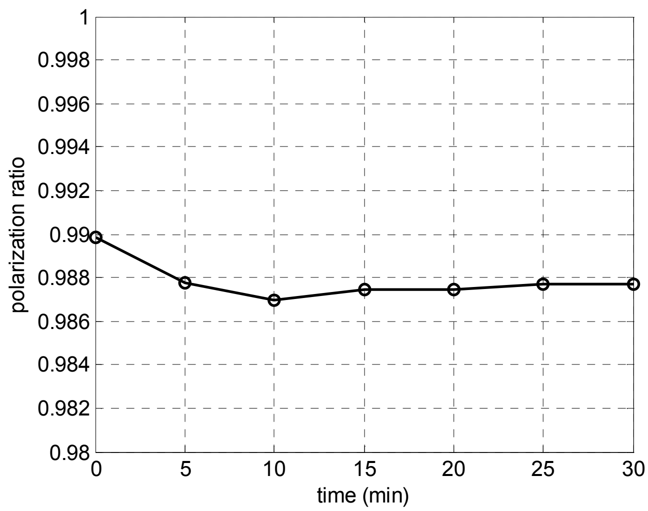

Figure 8. Polarization ratio as a function of time. XLA 300 running at 75% duty cycle, 6 kHz, 10 mJ per pulse. The laser was in standby state prior to time = 0.

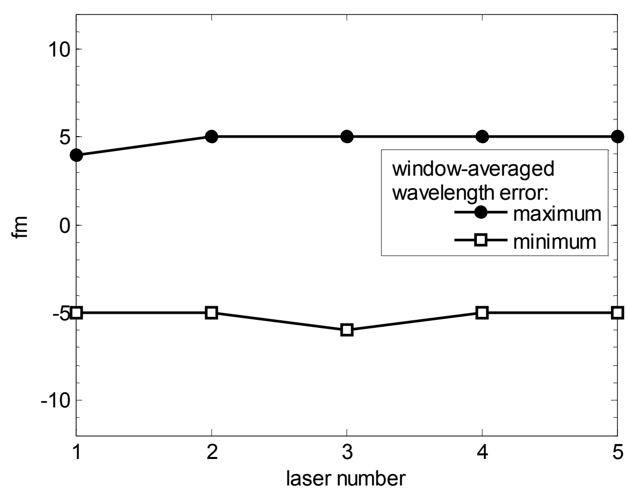

Figure 9. The extremes of window-averaged wavelength error as measured in a 100 Mpulse gas test and rep rate scans. 10 ms, 16 ms or 40 pulse window was used depending on the repetition rate.

accuracy of the onboard wavelength measurement is therefore less that 3.5 fm. This metrology error represents a small fraction of the overall wavelength stability budget. The overall wavelength stability as measured by the standard deviation of wavelength error is typically in the 20 to 25 fm range for XLA 300.

5. POLARIZATION AT HIGH OUTPUT POWER

The polarization purity of the laser output is becoming increasingly important at the same time as it is becoming more challenging to maintain it due to the higher power output requirements as polarized illuminator designs are introduced by scanner manufacturers. XLA 300 supports the same specifications for the polarization ratio as the previous XLA models, at the increased repetition rate and output power. Figure 8 shows the evolution of polarization ratio over a 30 minute operation at maximum duty cycle. The polarization ratio is defined as $(I_h - I_v)/(I_h + I_v)$; the ratio of one corresponds to pure horizontal polarization.

6. THERMAL MANAGEMENT

6 kHz operation required faster chamber gas circulation and an associated increase of fan power, as well as an increase in the power consumed by the solid-state pulse power system. The need for increased heat removal from the frame necessitated upgrading the capacity of the thermal management subsystem. The overall cooling water flow was increased and the parameters of the cooling circuits were optimized for efficient heat removal, while maintaining tight temperature control of chamber gas temperature over a wide range of duty cycles. Vent air flow requirements did not change compared to XLA 100 and 200.

7. MANUFACTURING DATA

Figure 9 shows the minimum and maximum window-averaged wavelength error measured on several XLA 300 units assembled and tested in pilot manufacturing. The data is derived from a standard manufacturing gas test including a variety of duty cycles and repetition rates and a standby period, and comprising about 100 million pulses each. The statistics of all the bandwidth values measured in the same tests is shown in Figure 10. The reproducibility of the E95% bandwidth from one laser system to the next is comparable to the unit-to-unit variability of ELIAS II spectrometers. The data demonstrate a robust design ready for volume production.

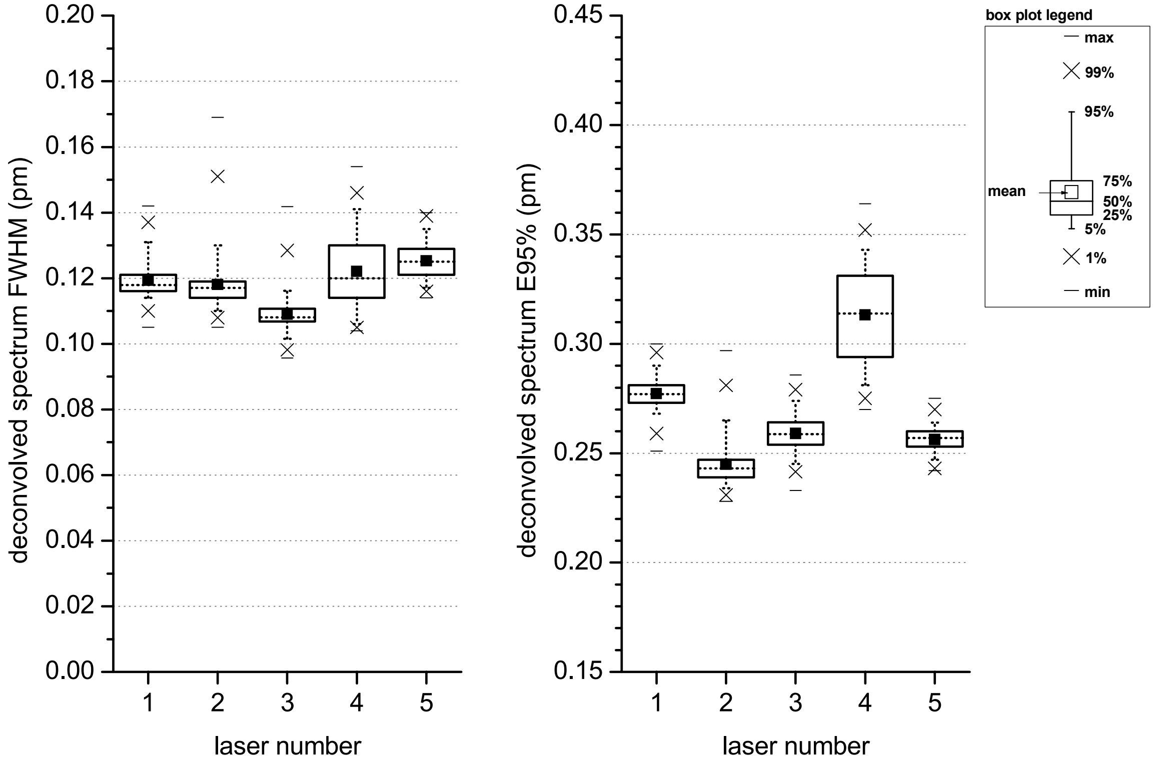

Figure 10. Bandwidth as measured in manufacturing tests. The data set for each laser includes high and low duty cycle repetition rate scans and a 100 Mshots gas test. LTB ELIAS II grating spectrometers were used.

8. CONCLUSIONS

XLA 300 is the industry's first production 193 nm light source operating at 6 kHz. It has completed acceptance testing in October 2005 and is now in production. Based on the versatile XLA platform, the light source is available in a number of configurations, including ultra-low bandwidth down to 0.25 pm E95%, or output power up to 90 W. The light source is designed for next generation immersion scanners.

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REFERENCES

1. R. Sandstrom, A. Ershov, V. Fleurov, "MOPA laser Architecture for High Power Lithographic Light Sources", SPIE 27th Conference on Microlithography, March 3—8, 2002, Santa Clara, CA, USA.
2. Vladimir B. Fleurov, Daniel J. Colon III, Daniel J. W. Brown, Patrick O'Keeffe, Herve Besaucele, Alexander I. Ershov, Fedor Trintchouk, T. Ishihara, Paolo Zambon, R. J. Rafac, and A. Lukashev, "Dual Chamber Ultra Line-Narrowed Excimer Light Source for 193 nm Lithography", *Optical Microlithography XVI*. Edited by Yen, Anthony. Proceedings of the SPIE, Volume 5040, pp. 1694-1703, 2003.

3. Toshihiko Ishihara, Herve Besaucele, Cynthia A. Maley, Vladimir B. Fleurov, Patrick O'Keeffe, Mary E. Haviland, Richard G. Morton, Walter D. Gillespie, Timothy S. Dyer, Bryan Moosman, and Robert Poole, "Long-term reliable operation of a MOPA-based ArF light source for microlithography", Optical *Microlithography XVII*. Edited by Bruce W. Smith. Proceedings of SPIE, Volume 5377, pp. 1858-1865, 2004.
4. Toshihiko Ishihara, Robert Rafac, Wayne J. Dunstan, Fedor Trintchouk, Christian Wittak, Richard Perkins, Robert Bergstedt, and Walter Gillespie, "XLA-200: the third-generation ArF MOPA light source for immersion lithography", *Optical Microlithography XVIII*, Bruce W. Smith, Editor, Proceedings of SPIE, Volume 5754, pp. 773-779, 2005.
5. Walter D. Gillespie, Toshihiko Ishihara, William N. Partlo, George X. Ferguson, and Michael R. Simon , "6 kHz MOPA light source for 193 nm immersion lithography", *Optical Microlithography XVIII*, Bruce W. Smith, Editor, Proceedings of SPIE, Volume 5754, pp. 1293-1303, 2005.
6. Tsukasa Hori, Takayuki Yabu, Takanobu Ishihara, Takayuki Watanabe, Osamu Wakabayashi, Akira Sumitani, Kouji Kakizaki, Hakaru Mizoguchi, "Feasibility study of 6 kHz ArF excimer laser for 193 nm immersion lithography", *Optical Microlithography XVIII*, Bruce W. Smith, Editor, Proceedings of SPIE Volume 5754, pp. 1285-1292, 2005
7. Robert J. Rafac, "Overcoming limitations of etalon spectrometers used for spectral metrology of DUV excimer light sources", *Optical Microlithography XVII*, Bruce W. Smith, Editor, Proceedings of SPIE, Volume 5377, pp. 846-858, 2004.